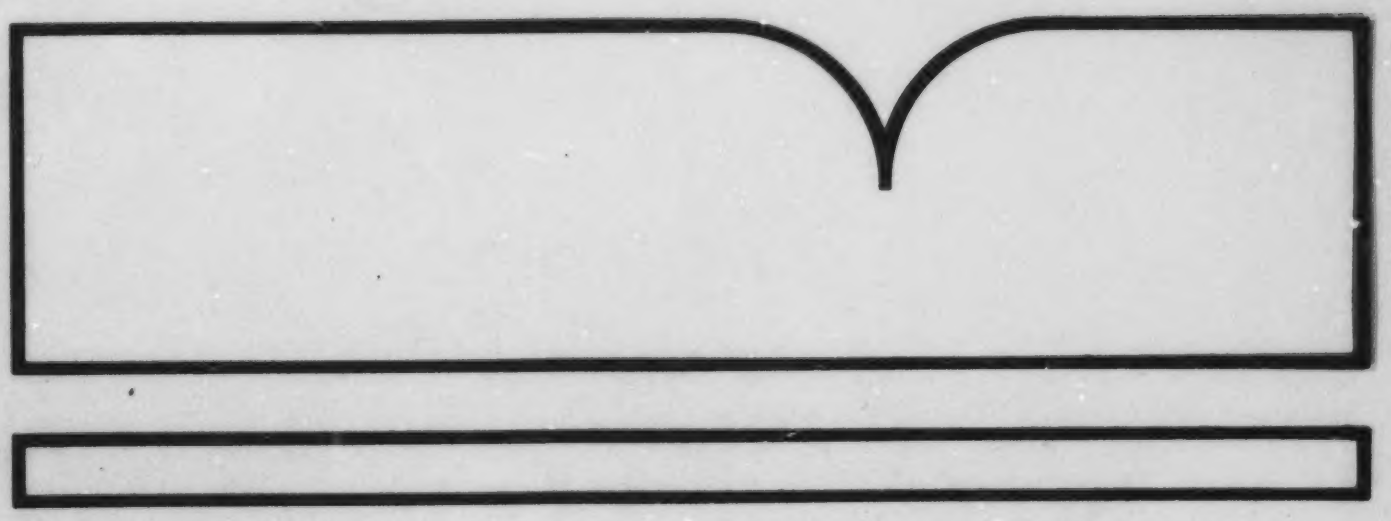
PB84-169325

Chemical and Physical Characterization of Municipal Sludge Incinerator Emissions

(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC

Mar 84



U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-169325

EPA-600/3-84-047
March 1984

CHEMICAL AND PHYSICAL CHARACTERIZATION OF MUNICIPAL SLUDGE INCINERATOR EMISSIONS

by

Roy L. Bennett, Kenneth T. Knapp, and Donald L. Duke
Emission Measurement and Characterization Division
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/3-84-047		PB84 169325

4. TITLE AND SUBTITLE	5. REPORT DATE
CHEMICAL AND PHYSICAL CHARACTERIZATION OF MUNICIPAL SLUDGE INCINERATOR EMISSIONS	March 1984
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Roy L. Bennett, Kenneth T. Knapp, and Donald L. Duke	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Emissions Measurement and Characterization Division Environmental Sciences Research Laboratory Research Triangle Park, North Carolina 27711	CDTA1D/02-2210 (FY-84)
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Sciences Research Laboratory-RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711	Final 10/79-9-81
	14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Particulate emissions form a group of municipal sludge incinerators, three with multiple-hearth furnaces and one with a fluidized-bed furnace, were characterized. Objectives of the investigation were 1) to obtain specific elemental emission concentrations, and 2) to provide source inventories and source signatures, especially in terms of particle size, that would assist in the development and evaluation of source apportionment models. Three of the plants investigated in this study operated at or near autogenous burning conditions. Chemical element composition was determined for total and sized emission samples by x-ray fluorescence analysis. During this study considerable enrichment of several elements (S, V, Cu, Zn, Cd, Sn, and Pb) in the particulate emissions, relative to their content in the sludge, was observed. The largest average enrichment ratios were observed for cadmium (31), zinc (14), lead (9), and sulfur (8).

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	59
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

Particulate emissions from a group of municipal sludge incinerators, three with multiple-hearth furnaces and one with a fluidized-bed furnace, were characterized. Objectives of the investigation were (1) to obtain specific elemental emission concentrations, and (2) to provide source inventories and source signatures, especially in terms of particle size, that would assist in the development and evaluation of source apportionment models. Three of the plants investigated in this study operated at or near autogenous burning conditions. Chemical element composition was determined for total and sized emission samples by x-ray fluorescence analysis. During this study, considerable enrichment of several elements (S, V, Cu, Zn, Cd, Sn and Pb) in the particulate emissions, relative to their content in the sludge, was observed. The largest average enrichment ratios were observed for cadmium (31), zinc (14), lead (9), and sulfur (8). This report covers a period from October 1, 1979 to June 30, 1981, and work was completed as of September 30, 1981.

CONTENTS

Abstract iii
Figures vi
Tables vii
Acknowledgment ix

1. Introduction 1
2. Conclusion and Recommendations 4
3. Incineration Process Description 6
    Incinerator O 6
    Incinerator P 7
    Incinerator Q 8
    Incinerator R 9
4. Experimental Procedures 13
    Sampling procedures 13
    Analytical methods 14
5. Results and Discussion 18
    Sludge content 18
    Elemental emissions 19
    Total particulate and sulfur oxides 20
    Nitrogen oxides and hydrocarbons 20
    Particle size distribution 20

References 32
Appendices

A. Incinerator operating conditions 33
B. Particulate emission data 38
C. Sulfur dioxide and sulfuric acid mist emissions data 43
D. Nitrogen oxides emissions data 48

FIGURES

Number		Page
1	Schematic flow diagram of municipal sludge incinerators	11
2	Cross section of fluidized-bed furnace	12
3	Particulate sampling train	15
4	Sampling train for collecting characterization samples	16
5	Particle size distribution of zinc, phosphorus, iron, and total particulate emissions from Incinerator O	22
6	Particle size distribution of cadmium, calcium, and total particulate mass before the scrubber, and total particulate emission after the scrubber at Incinerator R	23

TABLES

Number		Page
1	Furnace Types, Control Systems, and Sludge Loadings	3
2	Elemental Composition (Percent) of Municipal Wastewater Sludge	24
3	Change of Elemental Composition (Percent) of Sludge from Incinerator O with Heating	25
4	Mean Concentrations of Elemental Emissions ($\mu g/Nm^3$) from Municipal Sludge Incinerators	26
5	Mean Composition (Percent of Total Mass) of Elements in Particulate Emissions from Municipal Sludge Incinerators	27
6	Enrichment Ratios of Elements in Emissions Relative to Content in Sludge	28
7	Mean Concentrations of Elements (mg/Nm^3) in Airborne Particulate Matter at Inlet to Scrubbers	29
8	Emission Rates and Concentrations of Total Particulate Mass and Sulfur Oxide Gases	30
9	Concentrations of Nitrogen Oxides and Hydrocarbons (ppm) in Sludge Incinerator Emissions	31
10	Summary of Incinerator O Operating Data	34
11	Summary of Incinerator P Operating Conditions	35
12	Summary of Incinerator Q Operating Data	36
13	Summary of Incinerator R Operating Data	37
14	Summary of Particulate Emissions - Incinerator O	39
15	Summary of Particulate Emissions - Incinerator P	40
16	Summary of Particulate Emissions - Incinerator Q	41
17	Summary of Particulate Emissions - Incinerator R	42
18	Summary of Sulfur Dioxide and Sulfuric Acid Mist Emissions - Incinerator O	44

Number		Page
19	Summary of Sulfur Dioxide and Sulfuric Acid Mist Emissions - Incinerator P	45
20	Summary of Sulfur Dioxide and Sulfuric Acid Mist Emissions - Incinerator Q	46
21	Summary of Sulfur Dioxide and Sulfuric Acid Mist Emissions - Incinerator R	47
22	Nitrogen Oxides Emissions	48

ACKNOWLEDGMENTS

The services of personnel from Engineering Sciences, Inc., of McLean, Virginia, are acknowledged for the field sampling at the four incinerators. Chemical elemental analyses were made at the Stationary Source Emissions Research Branch, U.S. Environmental Protection Agency, X-Ray Fluorescence Laboratory which is operated by Robert Kellogg and Nancy Roache of Northrop Services, Inc. The authors also gratefully acknowledge the valuable discussion and the assistance with preparation of sludge and ash samples of Howard Wall, Municipal Environmental Research Laboratory, EPA, Cincinnati, Ohio.

SECTION 1

INTRODUCTION

With the production of municipal wastewater sludge on a definite increase, an attendant increase is expected in the use of incineration for sludge disposal. A study was conducted to characterize particulate emissions from the stacks of a group of municipal sludge incinerators, three with multiple-hearth furnaces and one with a fluidized-bed furnace. One purpose of the investigation was to provide information on the concentration of chemical elements, especially heavy metals such as cadmium (Cd) and lead (Pb), in the emissions.

Because municipal sludges result from diverse manufacturing activities as well as from human excreta and food residues, the chemical compositions of these sludges vary with location and time. Thus, as Furr, et al. demonstrated in their analyses of the municipal sludge from 16 cities (1), no "typical" sludge exists. Enrichment of some elements, notably Cd and Pb, can occur in the incinerator emissions, relative to the concentration of these elements in the sludge feed. Therefore, if predictions about the character of stack emissions are based solely on sludge content, these predictions are likely to be erroneous.

During this study, representative emission samples were collected for: (1) particulate mass emission determination, (2) chemical characterization, and (3) particle size determinations. Particle size distributions were determined for both total mass emissions and for emissions of individual chemical elements. Emissions of sulfur dioxide, sulfuric acid, hydrocarbons,

and nitrogen oxides were determined. At each plant, process samples of the sludge feed were collected and analyzed. At the three multiple-hearth plants, some sampling was also conducted before the scrubber. However, similar sampling was prevented at the fluidized-bed plant (Incinerator Q) because of adverse temperature and pressure at the scrubber inlet. Table 1 summarizes the operating parameters of the four incinerator facilities during the test periods; a more detailed description of operating conditions appears in Appendix A.

This investigation was sponsored jointly by two U.S. Environmental Protection Agency Laboratories: The Environmental Sciences Research Laboratory of Research Triangle Park, North Carolina and the Municipal Environmental Research Laboratory of Cincinnati, Ohio.

TABLE 1. FURNACE TYPES, CONTROL SYSTEMS, AND SLUDGE LOADINGS

Incinerator designation	Furnace type	Control equipment	Average load of unit tested (kg/hr) (dry)	Sludge	
				Percent moisture	Percent volatile
O	Seven-chambered multiple hearth	Wet, tray-type scrubber	1940	63.5	74.5
P	Eight-chambered multiple hearth	Wet, tray-type scrubber	1740	49.3	54.1
Q	Fluidized bed	Wet, tray-type scrubber	838	66.2	69.2
R	Seven-chambered multiple hearth	Single-pass cyclone scrubber	1890	71.3	35.0

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Emissions from four municipal wastewater sludge incinerators, three multiple-hearth and one fluidized-bed, were characterized. The total particulate emissions, particle size distribution, sulfur oxides, elemental content, and nitrogen oxides were measured. The elemental composition of the feed stock sludge and the bottom ash was determined also. The distribution of elements in the emissions differs considerably from the distribution in the sludge, apparently due to the volatility of some elements, notably Cd, Pb and Zn. Cadmium had the highest average enrichment ratio (percent in emissions/percent in sludge), with a 31-fold increase. Enrichment occurs because more small particles than large particles escape through the control devices and the more volatile elements form, or condense on, small particles.

Average mass median diameters of the particles emitted from all four incinerators were small, ranging from 0.28 to 1.1 μm. Few particles were larger than 2 μm. Most of the volatile elements were found in the submicron-particle range.

Because the composition of municipal sludge fluctuates from city to city, and since enrichment factors for the more volatile elements were found to vary greatly from one incinerator to another, it does not appear feasible to describe a precise, representative emission profile for sludge incinerators as a group. Nevertheless, information obtained in this study should be useful for source apportionment modeling and for environmental impact assessment.

Only limited information is available regarding the organic compounds emitted from sludge incinerators. Further studies to identify and measure specific organic compounds are recommended.

SECTION 3

INCINERATION PROCESS DESCRIPTION

A schematic flow diagram for municipal sludge incinerators is presented in Figure 1. Incinerator types, emission control systems, and average sludge loadings for the four facilities examined during this study are summarized below.

INCINERATOR O

Incinerator O, which has been operating since 1975, has two tandem seven-chamber hearth furnaces. During normal conditions only one of these two furnaces is in operation; the furnace designated as Unit No. 2 was tested during this program. The normal sludge incineration feed rate ranges from 7,000 lbs/hr during summer operations to 12,000 lb/hr during winter operations. Operating data collected during the test program, listed in Appendix A, indicate a fairly stable sludge flow to the unit throughout testing. Maximum operating load was maintained throughout the testing period, except for Friday (11/30/79), when the average sludge input was 3/4 ton/hr lower than the maximum. Supplemental fuel oil was used once; this occurred on Wednesday (11/28/79) between 1600 and 1800 hrs, when an insignificant 16 gal was consumed. During the remainder of the testing, the sludge burned autogenously, combusting on its own with no need for supplementary fuel.

Properly preparing the sludge for combustion is important for insuring efficient, cost-effective incineration. Incoming raw sludge is processed first through thickening; it is then thermally conditioned through a pressure and

heat process which breaks the sludge solids into smaller particles that which may be dewatered more easily. The sludge particles are then fed onto drum-type vacuum filters, where a sludge cake is produced. This cake is moved by conveyor belt and deposited into the top of the incinerator chamber. An intermittently-rotating rake assembly then carries burning sludge downward through each hearth. These rotating rakes insure more complete burning by moving the sludge from inner to outer areas of one hearth, back toward the center of the next hearth as the sludge cake passes downward. Combustion air, which is supplied to the unit via induced draft, is controlled by dampers located around the chamber perimeter. Ash is removed by truck to a landfill.

Combustion gases exit the incinerator through a refractory-lined steel duct at the top of the reactor. At the incinerator outlet the gases split into two streams, one flowing through a precooler and the other passing to a waste heat recovery boiler. (Steam from the waste heat recovery boiler is used in the sludge thermal conditioning process.) These two gas streams then enter the scrubber from separate ducts. Scrubber exhausts pass through an induced-draft fan and on to the stack. Prior to stack entry, the scrubber exhausts are diluted by center shaft and shell cooling air that enters the breeching just upstream of the scrubber outlet sampling ports.

INCINERATOR P

Incinerator P has a single, eight-hearth rotating rake furnace. The sludge combustion process is supplemented by the use of natural gas, with burners located in hearth numbers 2, 4, 6, and 8. Incinerator P normally operates about four days per week on a 24-hour basis, until the sludge supply is exhausted. The sludge incineration feed rate ranges from 6,000 lbs/hr to 10,500 lbs/hr wet. During the test program, the sludge feed averaged 6,708 lbs/hr on Thursday (12/6/79) and 8,625 lbs/hr on Friday (12/7/79). At no time

during the testing did the sludge achieve an autogenous burn. Combustion was aided by natural gas used at the average rate of 43.8 ft^3 and 39.9 ft^3 on Thursday and Friday, respectively.

Raw sludge is processed through thickening, then conditioned with pressure and heat to produce smaller particles that are dewatered more easily. The sludge is then fed to drum-type vacuum filters, where a sludge cake is produced. This cake is moved by conveyor belt and deposited into the top of the incinerator chamber. The burning sludge is then carried downward through each hearth by a rotating shaft and rake assembly. The rakes help accomplish more complete burning by moving the sludge from inner to outer areas of one hearth and back toward the center of the next hearth. Combustion air is supplied by induced draft. Ash is removed to a storage hopper, then transported by truck to a landfill.

Combustion gases exit the incinerator through a rectangular refractory-lined duct, and pass directly to a waste heat recovery boiler producing 5,000 to 6,000 lbs/hr of steam used in the sludge thermal heat treatment process. The cooled gases then pass through a recirculation duct; part of the gases returns through the boiler, while the remainder passes to a venturi and to a closed loop, wet, tray-type scrubber system for particle removal. The gases then pass upward to a fan and are exhausted to the atmosphere. In addition, air used in the vacuum dryer system is vented into the waste heat boiler upstream of the incinerator exhaust. This process may provide higher hydrocarbon and mercaptan concentrations in the exhaust stream. Pertinent incinerator operating parameters maintained through the testing are listed in Appendix A.

INCINERATOR Q

Operation of the fluidized-bed furnace at Incinerator Q was started in 1978. As shown in Figure 2, the incinerator consists of a refractory-lined

vertical, cylinder-shaped vessel; a sand bed located in the lower section of the incinerator is supported by a grate. Dewatered sludge cake is injected above the grate and combustion air flows upward under pressure, fluidizing the mixture of hot sand and sludge. During the test periods, sand bed differential pressures ranged from 37 in. H_2O to 45 in. H_2O. Supplemental No. 2 fuel oil is supplied through burners above and below the bed. Combustion air is preheated by electric coils to a temperature of 950°F, with combustion of the sludge occurring between 1400-1500°F. Ash is removed from the unit after passing through the cooling venturi where it is mixed with the scrubber water outflow, then removed to a sediment tank.

Heat necessary for raising the sludge to its combustion temperature is derived from the reservoir of heat in the reactor bed. Mixing of fuel oil and sludge through the entire bed, along with optimum contact of oxygen from the forced draft, insures rapid combustion. Organic particles are retained by the bed and reduced to mineral ash to prevent clinker build-up. The ash is carried into the exhaust by the upflow of gases and by the spent sand, which is reduced in size by the violent motion in the reactor. (This sand loss is measured at about 5-7 lbs per 8 hrs of operating time.)

Air flow to the reactor is controlled by an oxygen analyzer located downstream of the combustion zone. The auxiliary No. 2 fuel oil feed rate is controlled by reactor temperature sensors installed around the bed perimeter. Basic operating parameters measured during the test program are listed in Appendix A.

INCINERATOR R

In operation since 1969, Incinerator R has four seven-hearth furnaces. During normal conditions, all of the furnaces are in operation. The furnace designated as Unit No. 3 was tested during this program. Sludge incineration

feed rates ranged from 14-15 tons/hr during this test program, with about one-half of the sludge going to Unit No. 3. Operating data collected during the program, listed in Appendix A, indicate characteristic sludge flow to the unit throughout testing. No. 2 fuel oil, at approximately 40 gal/hr, supplemented combustion. The unit does not reach autogenous burning, nor is it designed for such operation.

Incoming raw sludge is processed through thickening. The sludge is then fed onto drum-type vacuum filters, where a sludge cake is produced. This cake is moved by conveyor belt and deposited into the top of the incinerator chamber. The burning sludge is carried downward through each hearth by an intermittently-rotating rake assembly, which moves the sludge from inner to outer areas of one hearth, then back toward the center of the next hearth. Combustion air is supplied to the unit via induced draft, and controlled by dampers around the chamber perimeter. Some ash is recycled through the incinerator to aid combustion; the remainder is transported to landfills.

Combustion gases exit the incinerator through refractory-lined steel ducts located at the top of the reactor, then flow from the incinerator to a common breeching and stack.

Operating parameters for Incinerator R, measured during the testing period, appear in Appendix A.

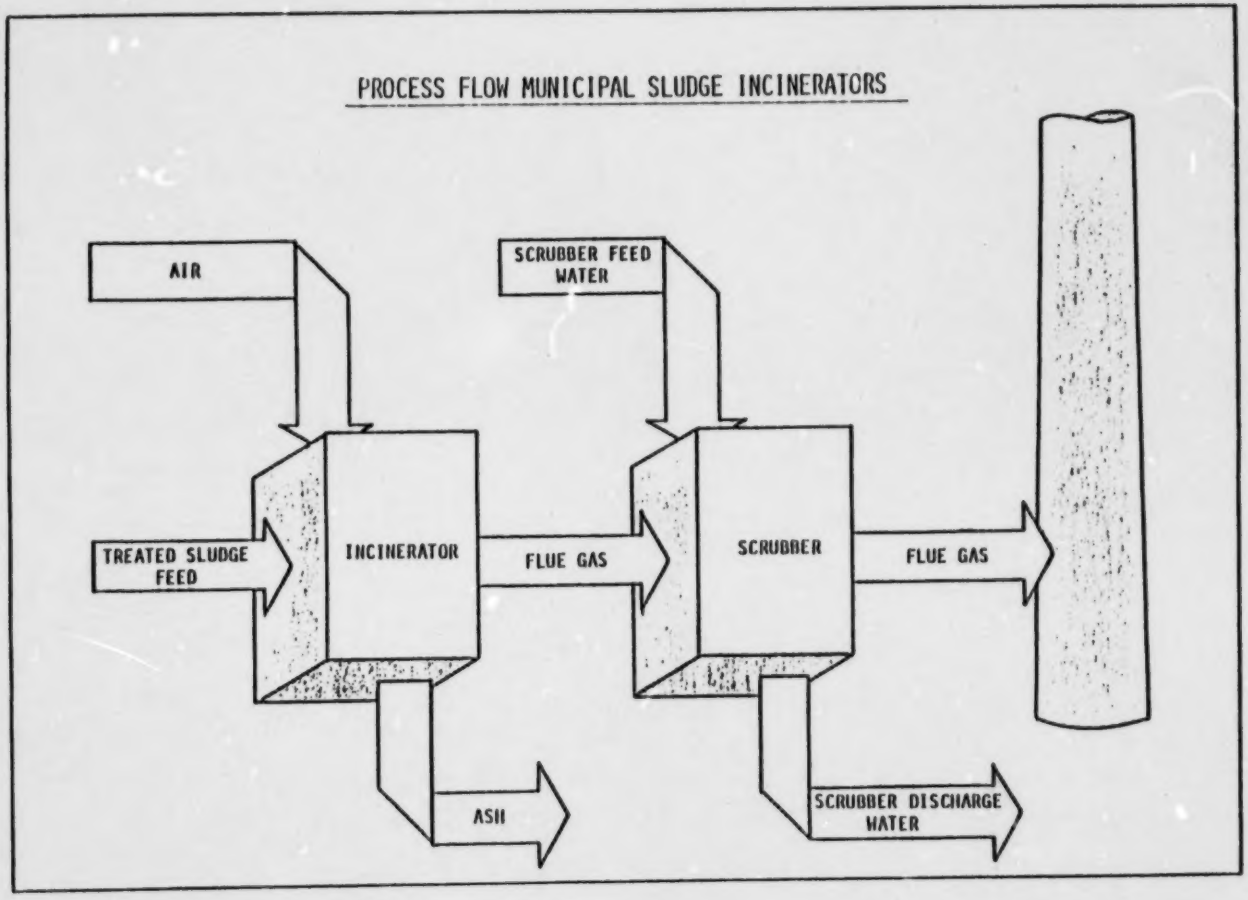


Figure 1. Schematic flow of municipal sludge incinerators.

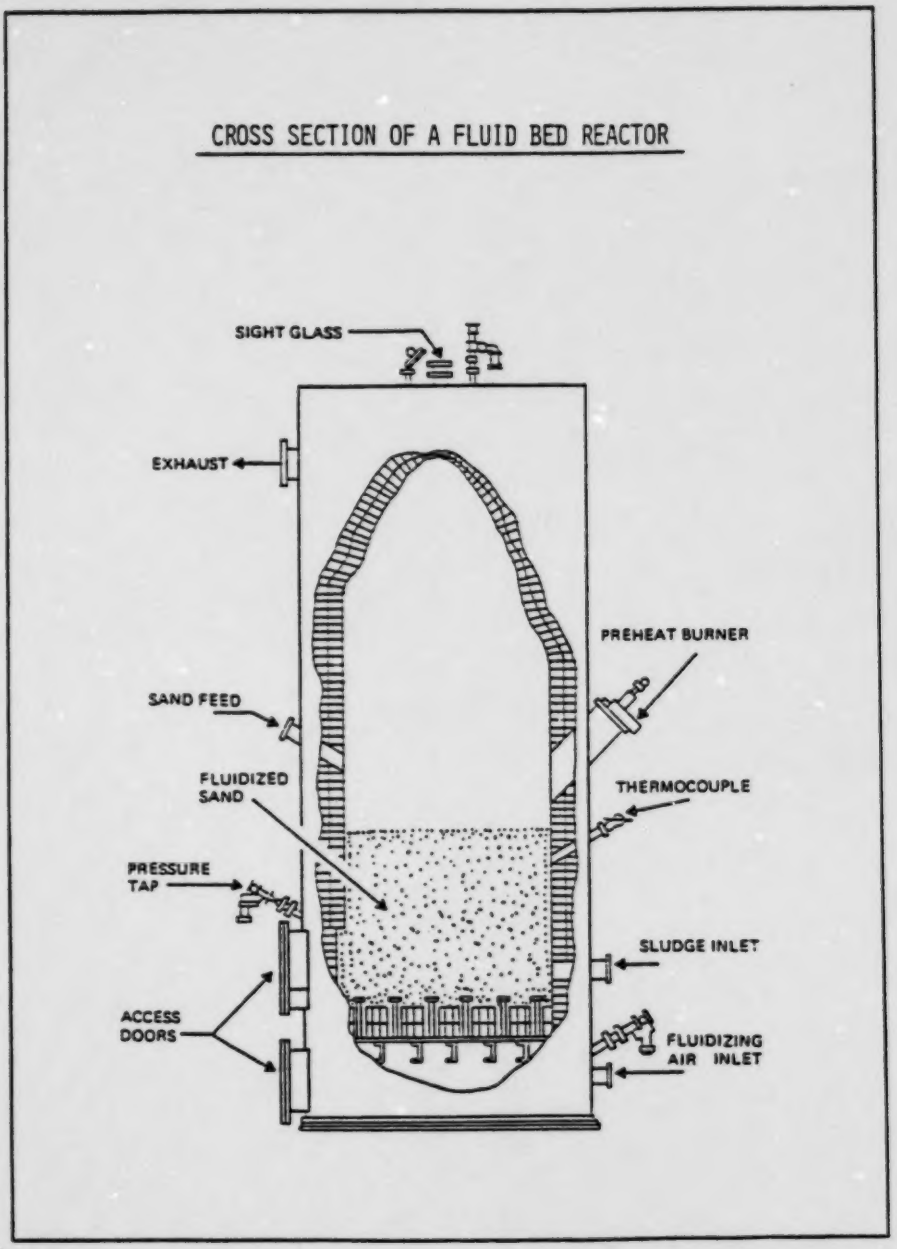


Figure 2. Cross section of fluidized-bed furnace.

SECTION 4

EXPERIMENTAL PROCEDURES

SAMPLING PROCEDURES

A standard U.S. Environmental Protection Agency (EPA) Method 5 sampling train (2) was used to collect particulate samples for mass emission rate determinations. The sampling train impingers, shown in Figure 3, were adapted for use in determining gaseous sulfur oxides by EPA Method 8 (3). The first impinger contained 150 mL of 80% isopropanol, which was followed by a high-purity glass wool plug in the U-tube between the first and second impingers. The second and third impingers contained 100 mL each of 5% hydrogen peroxide solution and the fourth impinger was filled with approximately 400 g of indicating silica gel. Prior to sampling, a velocity profile of the duct at the sampling location was determined through transversing with a Pitot tube system. A 5-ft heated, Pyrex-lined probe was used to obtain all Method 5 and Method 8 samples, collected at a single point determined to have the average velocity of the flue gas within the duct.

Samples used for chemical characterization by x-ray fluorescence analysis (XRF) were collected with a modified Method 5 train, as depicted in Figure 4. In this sampling train, the conventional sample box, filter holder, and glass impingers were replaced by an EPA-designed heated sample box housing a stainless steel filter holder for 47-mm filters. Samples for particulate characterization were collected in sets consisting of two Gelman A or Reeve Angel 900 AF glass fiber filters, two Millipore AA filters, one Nuclepore 0.8-μm filter, and six Teflon 0.2-μm filters. To provide a variety of loadings on the filters,

sampling periods ranged from 15 sec to 10 min. In all cases, an attempt was made to sample isokinetically. Following XRF analyses samples collected on Nuclepore and glass fiber filters were used for electron microscope examination.

University of Washington Mark III cascade impactors were used to collect samples for measuring the particle size distribution of both total mass emissions and of individual chemical elements. The impactor samples were taken in-stack at the point of average gas velocity; this same sampling point was used for the characterization sampling. Samples were collected isokinetically, with a sampling rate between 0.5 and 0.75 ft^3/min through the impactor.

Composite pre-burn sludge samples and post-burn ash were collected at all incinerators except at the fluidized-bed unit, where only sludge samples were taken. The sludge samples were heated to 600°C for 30 min to remove the volatile contents prior to chemical analysis.

During the testing period, each site was monitored on a continuous basis for nitrogen oxides and hydrocarbon emissions. A heated Teflon line delivered the samples to a Thermo Electron Model 44 Dual-Chamber, Single-Detector monitor for nitrogen oxides, and to a Scott Model 166 Total Hydrocarbon Analyzer with a single-flame ionization detector.

ANALYTICAL METHODS

Emission samples, as well as sludge and ash samples, were analyzed with a Siemens MRS-3 multichannel wavelength dispersive x-ray fluorescence spectrometer; the Siemens MRS-3 has 15 fixed-wavelength monochromators and a scanning channel that allows analysis for 11 additional elements. This system, which has been optimized for the analysis of aerosol samples (4), requires light, uniform deposits on low-mass substrates. The characterization samples collected on Teflon, Millipore and Nuclepore filters were analyzed directly. However, samples collected with the cascade impactors resulted in small piles on the

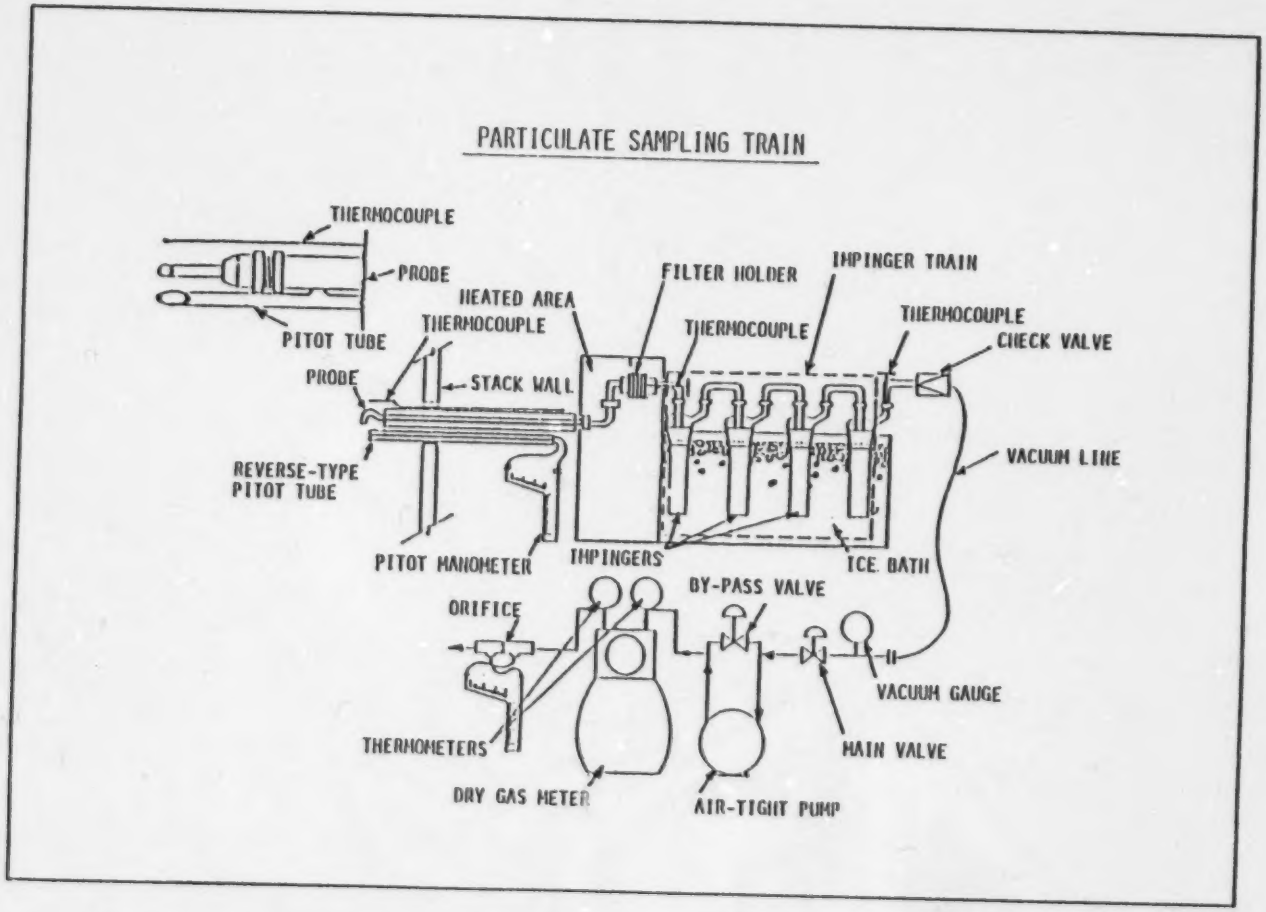


Figure 3. Particulate sampling train.

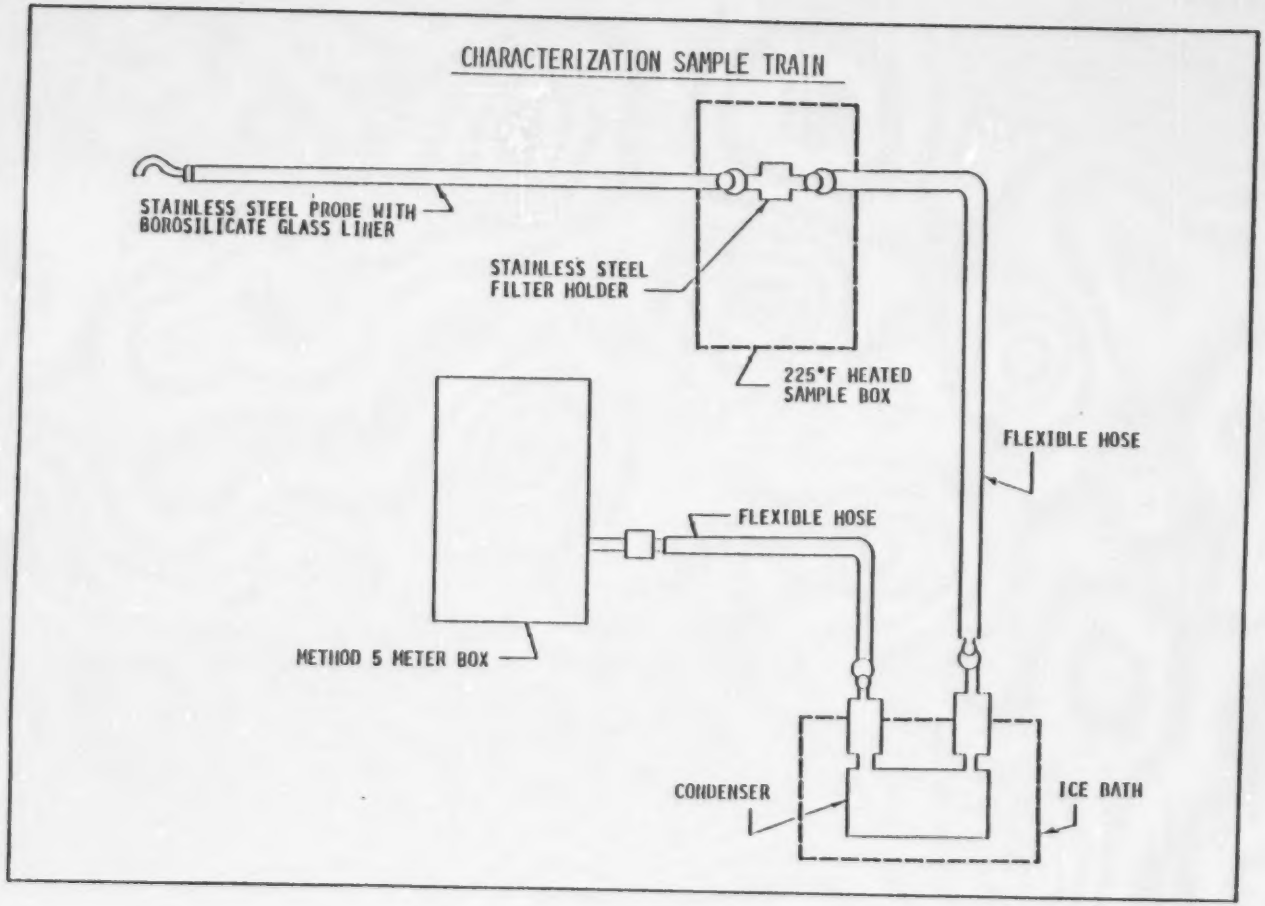


Figure 4. Sampling train for collecting characterization samples.

impactor stages which could not be analyzed directly. Therefore, material on each stage was suspensed in liquid, then redeposited on polycarbonate films (poreless Nuclepore) (5). Bulk samples such as the ashed process feed sludge, and the thick deposits on glass fiber filters, were processed into thin, carbowax films suitable for XRF analysis. These bulk samples were ground with an agate mortar pestle, then mixed with carbowax and solvent and ground further until the solvent dried. This mixture was transferred to a hydraulic press, where 10 tons of force was applied to form a flat specimen.

Solutions such as those obtained from the back-up impinger of Method 5 were analyzed by procedures recently developed in the ESRL Laboratory (6). A Collison nebulizer was used to generate liquid aerosols from the analyte solution. Adequate dilution air was added to dry the particles. Thin, uniform deposits suitable for analysis were collected on a filter located in the air stream after a small mixing chamber.

SECTION 5

RESULTS AND DISCUSSION

SLUDGE CONTENT

The elemental composition of the ashed sludge feed material, determined by XRF, is shown in Table 2. The values represent the averages for four to six composite samples taken during two- to three-day testing periods at each incinerator. The relative standard deviation was generally less than 10% for the more abundant elements, or those having a concentration greater than 1%. For comparison, the average content of sludge from 16 cities as determined by Furr et al. (1) is also listed in Table 2. To determine whether significant volatilization losses of the analyzed elements occurred during the ashing of sludge samples at 600°C, a group of samples was heated for 45 minutes (at the temperatures indicated in Table 3), then analyzed by XRF. Each element's concentration at 600°C was compared to its concentration in the 100°C dried sludge sample. Each concentration was normalized to that of a nonvolatile element (potassium) at the two temperatures. As shown in the last column of Table 3, the results from samples taken at Incinerator O indicate that, relative to potassium, only sulfur was significantly changed. Similar results were found with Incinerator P samples.

The non-volatile elemental content of post-burn bottom ash samples from the three multiple-hearth furnaces was essentially the same as that found in ashed sludge samples from those sites. No bottom ash was available at the fluidized-bed incinerator since the ash, which was less dense than the sand in the bed, was continuously swept out at the top of the reactor. Greenberg,

Zoller, and Gordon (7) recently reported an investigation on another fluidized-bed incinerator in which they examined the composition of ash collected at the scrubber bottom. For most elements, they found that a ratio of concentration in scrubber bottom ash/concentration in sludge was less than 1.0. This was due to a loss resulting when elements vaporized out of the sludge or dissolved into the scrubber solution.

ELEMENTAL EMISSIONS

The mean concentrations (micrograms per normal cubic meter) of the elements, determined by XRF, in the emissions from the four plants are shown in Table 4. The relative standard deviation of the samples analyzed (between 45 and 95 samples per site) to obtain each of these concentrations averaged 33%, 72%, 32%, and 68% for O, P, Q and R, respectively. The greater variability of P and R reflect the wider range of operating conditions; e.g., the rates of feed and stack gas flow during the testing periods. It is apparent immediately that elements such as Zn, Cd, and Pb had a higher concentration in the emissions than would have been expected based solely on their concentration in the sludge. Table 5 lists the average composition of the emission samples from each incinerator in per cent of the total mass. The concentrations of lead in the emissions have increased to about 3% from a mean concentration of 0.5% in the sludges. Enrichment factors, calculated by dividing the concentration in the total particulate emissions by the concentration in the sludge, are listed in Table 6.

At each of the four incinerators, characterization samples were also taken after the furnaces and before the scrubbers. The elemental concentrations, given in milligrams per normal cubic meter, are listed in Table 7.

TOTAL PARTICULATE MASS AND SULFUR OXIDES

The emission rates and concentrations of particulate mass, sulfur dioxide and sulfuric acid were obtained from the Method 5 and Method 8 tests run after the scrubber outlets. The emissions rates shown in Table 8 are the mean values obtained after running six to eight tests at each incinerator. Lowest particulate emissions were observed at the fluidized-bed incinerator, Q. The higher sulfur oxide emissions from Incinerator R were due presumably to the supplementary fuel oil burned to maintain combustion.

NITROGEN OXIDES AND HYDROCARBONS

The results from monitoring nitrogen oxides and total hydrocarbons are shown in Table 9. The sample values are 20-min averages of strip chart recordings; the averages shown represent the mean of all the 20-min averages. The average concentrations are similar at incinerators O, P and Q, but the nitrogen oxides are much lower at R; no measurement of hydrocarbons was made at R.

PARTICLE SIZE DISTRIBUTION

The average mass median diameters obtained from the particle size distribution measurements were 0.28, 0.30, 1.1 and 0.85 μm at incinerators O, P, Q and R, respectively. Individual size distributions for several elements, as well as the total mass distribution of typical samples taken at Incinerator O, are shown in Figure 5. For convenience, the largest and smallest size fractions have been assigned finite values. The Zn distribution, predominantly submicrometer particles, was characteristic of that of S, Cd, Pb, and other elements exhibiting enrichment in the emissions. Phosphorus exhibited a group of mid-range particles around 2 μm. Iron was distributed through all sizes, with a significant fraction of large particles evident even in the controlled, post-scrubber emissions. Only a small fraction of the total mass was greater than 2 μm (see Figure 5).

At Incinerator R, particle size measurements also were made before the scrubber. Figure 6 shows the distribution at the scrubber inlet. At the inlet, large particles were preponderant; but at the scrubber outlet, where smaller particles predominated because of the scrubbers' more efficient removal of larger particles, a second mode occurred near 2 μm. Evident in these pre-scrubber measurements is the contrast in the distribution of a more volatile element such as cadmium with that of calcium (see Figure 6).

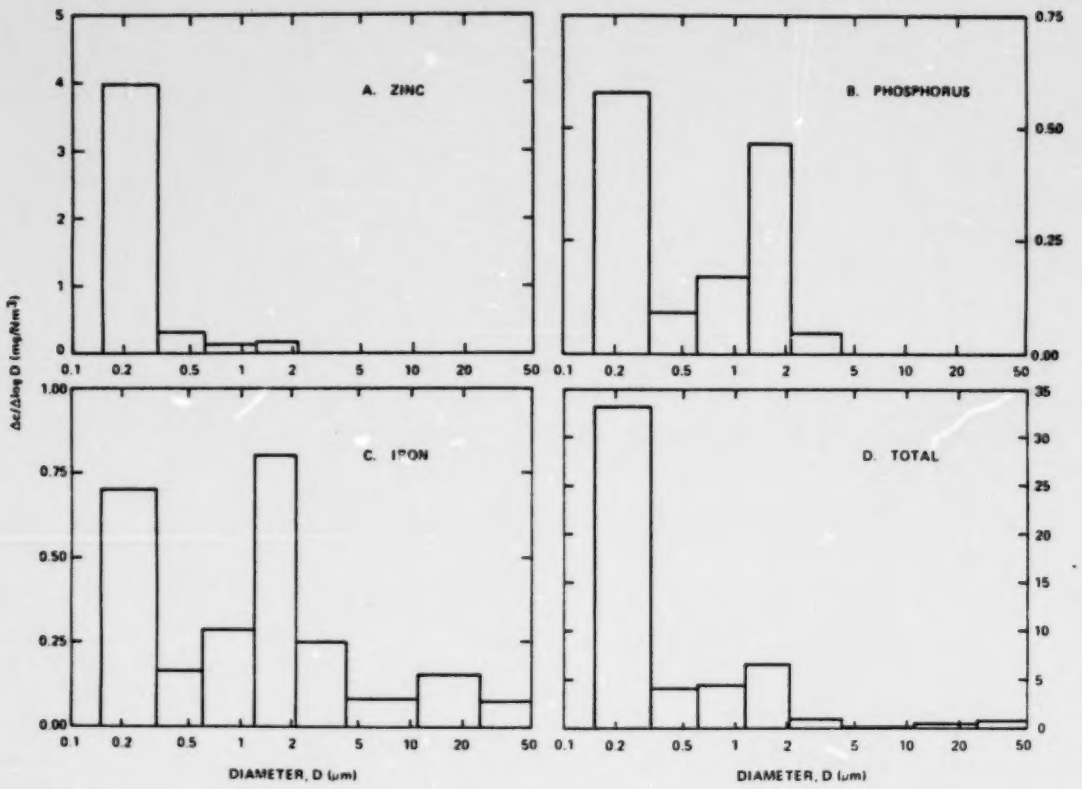


Figure 5. Particle size distribution of zinc, phosphorus, iron, and total particulate emissions from Incinerator O.

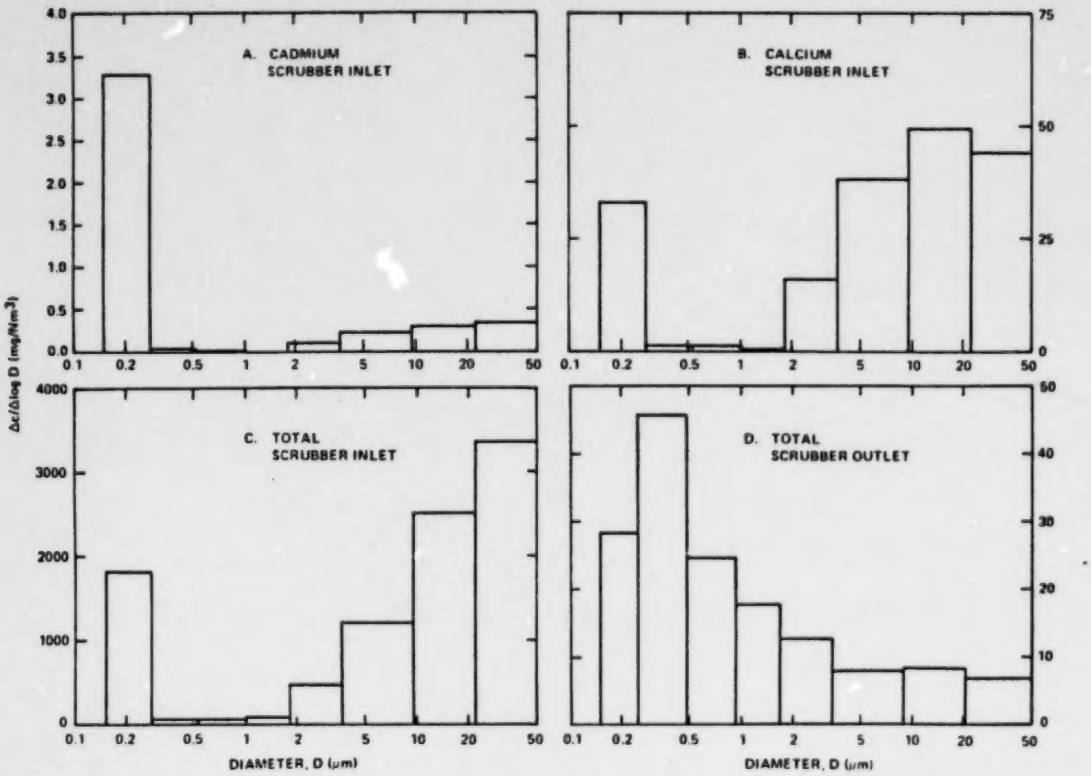


Figure 6. Particle size distribution of cadmium, calcium, and total particulate mass before the scrubber, and total particulate emission after the scrubber at Incinerator R.

TABLE 2. ELEMENTAL COMPOSITION (PERCENT) OF MUNICIPAL WASTEWATER SLUDGE

Element	Site O		Site P		Site Q		Site R		Avg. Content 16 cities (a)
	AV	SD	AV	SD	AV	SD	AV	SD	
Na	1.0	0.09	0.7	0.11	<0.6		<0.2		0.44
Mg	1.8	0.08	1.0	0.17	0.87	0.13	0.92	0.03	0.60
Al	3.4	0.28	3.6	0.47	4.0	0.23	5.2	0.14	1.83
Si	10.1	0.46	13.0	3.3	17.0	2.7	12.0	0.34	--
P	6.4	0.44	4.4	0.22	4.1	0.13	3.7	0.12	1.56
S	0.93	0.15	1.3	0.41	0.82	0.46	0.47	0.06	--
Cl	0.45	0.01	0.08	0.18	<0.5		0.68	0.19	0.38
K	1.3	0.09	1.1	0.24	1.2	0.15	1.1	0.02	1.22
Ca	17.	0.62	6.2	1.2	7.5	1.0	9.8	0.15	3.62
Ti	0.84	0.06	0.76	0.05	0.77	0.04	1.18	0.04	0.23
V	0.03	0.01	0.04	0.01	0.03	0.01	<0.01		0.004
Cr	0.22	0.02	0.50	0.27	0.22	0.24	0.38	0.02	0.14
Mn	0.70	0.11	0.23	0.11	0.34	0.12	0.11	0.008	0.019
Fe	6.7	1.0	17.	7.9	7.6	6.4	5.4	0.10	3.06
Co	0.01	0.003	0.03	0.02	0.01	0.02	0.01	0.002	0.001
Ni	0.03	0.01	0.14	0.08	0.06	0.07	0.06	0.008	--
Cu	0.12	0.02	0.75	0.43	0.27	0.37	0.44	0.02	0.13
Zn	0.30	0.04	1.1	0.08	1.0	0.07	1.4	0.03	0.21
As	<0.3		<0.3		<0.03		<0.03		0.0014
Se	<0.04		<0.04		<0.04		<0.04		0.0003
Br	<0.05		<0.05		<0.05		<0.05		0.005
Cd	0.02	0.005	0.04	0.05	0.08	0.04	0.03	0.005	0.010
Sn	0.30	0.02	0.25	0.03	0.25	0.03	0.19	0.006	0.022
Sb	0.03	--	0.02	0.004	0.01	0.001	0.01	0.001	0.001
Ba	0.25	0.02	0.41	0.11	0.45	0.04	0.27	0.01	0.06
Pb	0.34	0.13	0.48	0.18	0.59	0.25	0.23	0.03	0.18

(a) Reference 1.

TABLE 3. CHANGE OF ELEMENTAL COMPOSITION (PERCENT) OF SLUDGE FROM INCINERATOR O WITH HEATING

Element	100°C	200°C	400°C	600°C	800°C	1000°C	Normalized Enrichment (a)
Mg	0.53	0.60	1.5	1.6	1.8	1.9	0.98
Al	0.86	0.86	2.4	2.4	2.8	2.9	0.89
Si	2.5	2.4	7.7	7.4	8.8	9.2	0.94
P	1.6	1.6	4.5	4.5	4.9	5.3	0.89
S	0.54	0.59	0.88	0.86	0.91	0.64	0.50
K	0.33	0.32	1.0	1.0	1.1	1.2	1.00
Ca	4.1	4.1	12.6	12.2	13.7	14.8	0.93
Ti	0.21	0.19	0.60	0.60	0.64	0.68	0.91
Cr	0.07	0.11	0.23	0.23	0.24	0.20	1.04
Mn	0.22	0.18	0.60	0.58	0.66	0.66	0.84
Fe	1.9	1.8	6.1	6.4	6.7	7.2	1.07
Co	--	--	--	0.01	0.01	0.01	--
Ni	--	--	0.03	0.04	0.04	0.04	--
Cu	0.04	--	.11	0.13	0.13	0.13	1.09
Zn	0.09	0.08	0.29	0.31	0.33	0.32	0.97
Cd	--	--	0.01	0.02	0.02	0.02	--
Sn	0.09	0.09	0.24	0.24	0.28	0.27	0.85
Ba	0.06	0.05	0.19	0.18	0.21	0.20	0.95
Pb	--	--	0.24	0.24	0.29	0.15	--

(a) Enrichment at 600°C relative to potassium: (% element/% potassium) at 600°C divided by (% element/% potassium) at 100°C.

TABLE 4. MEAN CONCENTRATIONS OF ELEMENTAL EMISSIONS ($\mu g/Nm^3$) FROM MUNICIPAL SLUDGE INCINERATORS

Element	Site O		Site P		Site Q		Site R	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Na	350	110	290	230	100	50	240	170
Mg	90	32	440	550	51	18	21	6
Al	128	47	1570	1980	160	48	37	20
Si	590	100	4180	4826	270	80	620	290
P	590	120	1730	1890	210	69	570	350
S	660	300	930	410	730	270	2610	910
Cl	230	90	130	110	47	65	1990	2280
K	210	90	460	500	54	22	120	110
Ca	780	170	2620	2660	440	150	160	88
Ti	28	12	450	460	33	10	16	21
V	~35		38	14	9	2	<6	
Cr	97	39	480	330	14	8	230	106
Mn	27	13	82	30	23	8	10	1
Fe	370	80	7070	8170	228	71	230	145
Co	<6		25	8	<6		<6	
Ni	<22		125	121	<22		<22	
Cu	85	29	810	690	14	4	520	310
Zn	810	220	1840	1240	87	28	1830	1650
As	<29		<29		<29		<29	
Se	~45		20	3	18	17	26	1
Br	~49		57	19	39	17	170	140
Cd	42	15	34	15	7	2	1890	1410
Sn	180	51	1230	450	30	9	790	640
Sb	6	2	23	7	<2		43	40
Ba	10	4	290	280	20	7	14	15
Pb	510	190	1170	530	114	65	2140	1880

TABLE 5. MEAN COMPOSITION (PERCENT OF TOTAL MASS) OF ELEMENTS IN PARTICULATE EMISSIONS FROM MUNICIPAL SLUDGE INCINERATORS

Element	Site			
	O	P	Q	R
Na	2.76	0.57	1.96	0.34
Mg	0.71	0.86	1.01	0.03
Al	1.02	3.05	3.07	0.05
Si	4.69	8.13	5.33	0.91
P	4.69	3.36	4.14	0.84
S	5.25	1.80	14.42	3.83
Cl	1.80	0.26	0.93	2.91
K	1.71	0.89	1.07	0.18
Ca	6.20	5.09	8.76	0.23
Ti	0.22	0.88	0.65	0.02
V	0.28	0.07	0.18	--
Cr	0.77	0.94	0.28	0.33
Mn	0.21	0.16	0.46	0.01
Fe	2.91	13.75	4.52	0.34
Co	--	0.05	--	--
Ni	--	0.24	--	--
Cu	--	1.58	0.28	0.77
Zn	6.44	3.58	1.72	2.69
Se	--	0.04	0.36	0.04
Br	--	0.11	0.77	0.26
Cd	0.33	0.07	0.13	2.77
Sn	1.42	2.39	0.59	1.16
Sb	0.05	0.05	--	0.06
Ba	0.08	0.56	0.40	0.02
Pb	4.07	2.27	2.26	3.14

TABLE 6. ENRICHMENT RATIOS OF ELEMENTS IN EMISSIONS RELATIVE TO CONTENT IN SLUDGE

Element	Incinerator				Average enrichment
	O	P	Q	R	
Na	2.76	0.81	--	--	--
Mg	0.42	0.86	1.16	0.03	0.38
Al	0.30	0.85	0.78	0.01	0.49
Si	0.46	0.63	0.31	0.08	0.37
P	0.73	0.76	1.01	0.23	0.68
S	5.64	1.38	17.6	8.14	8.19
Cl	4.00	0.63	--	4.28	2.97
K	1.32	0.81	0.89	0.16	0.80
Ca	0.36	0.82	1.16	0.023	0.59
Ti	0.26	1.16	0.84	0.02	0.62
V	9.33	1.75	6.0	--	5.69
Cr	3.50	1.88	1.27	0.87	1.88
Mn	0.30	0.70	1.35	0.10	0.61
Fe	0.43	0.81	0.59	0.06	0.54
Co	--	1.67	--	--	--
Ni	--	1.71	--	--	--
Cu	5.67	2.11	7.0	1.75	4.13
Zn	21.47	3.25	28.7	1.89	13.83
Br	--	--	7.7	--	--
Cd	16.50	7.0	1.6	98.9	31.
Sn	4.73	9.56	2.36	6.10	5.68
Sb	1.67	2.50	--	4.6	2.92
Ba	0.32	1.36	0.89	0.07	0.66
Pb	11.97	4.70	3.83	13.65	8.53

TABLE 7. MEAN CONCENTRATIONS OF ELEMENTS (mg/Nm^3) IN AIRBORNE PARTICULATE MATTER AT INLET TO SCRUBBERS

Element	Site O		Site P		Site Q		Site R	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Na	2.00	0.45	2.15	0.84	8.19	1.92	2.54	1.34
Mg	5.25	10.71	3.70	1.23	25.40	8.96	4.11	2.44
Al	9.29	2.59	13.09	3.70	111.16	2.78	18.27	12.29
Si	24.06	6.69	33.95	9.51	268.51	91.64	42.33	22.38
P	20.06	5.30	12.35	3.25	124.35	55.49	17.43	9.74
S	3.78	1.10	2.28	0.82	10.66	6.69	4.46	2.08
Cl	0.80	0.40	0.56	0.27	1.99	1.48	5.07	4.58
K	4.32	1.37	3.76	1.10	28.12	8.50	5.78	3.36
Ca	53.28	14.95	19.44	5.45	263.45	101.36	55.81	29.41
Ti	2.43	0.90	3.16	0.86	20.10	6.50	6.24	4.96
V	0.010	0.006	0.14	0.05	0.83	0.35	0.23	0.14
Cr	0.76	0.30	2.86	0.81	2.88	0.96	2.35	1.57
Mn	1.74	0.92	0.36	0.15	12.68	4.11	0.65	0.49
Fe	26.76	8.53	60.74	16.83	162.67	57.34	34.96	25.22
Co	0.082	0.039	0.11	0.04	0.37	0.11	0.11	0.07
Ni	0.21	0.08	1.64	1.55	1.20	0.42	0.68	0.49
Cu	0.93	0.35	6.18	1.57	5.98	2.03	5.28	2.87
Zn	3.38	1.05	13.54	3.72	46.20	16.07	17.65	8.61
As	<0.03		<0.03		<0.03		<0.03	
Se	<0.02		<0.02		<0.02		<0.02	
Br	<0.05		0.18	0.07	0.62	0.33	0.39	0.24
Cd	0.16	0.04	0.23	0.07	4.16	3.57	4.04	2.65
Sn	1.11	0.40	3.08	0.73	6.81	1.56	2.00	1.01
Sb	0.11	0.06	0.067	0.021	0.57	0.40	0.15	0.08
Ba	0.73	0.25	2.00	0.55	12.59	3.41	1.53	1.10
Pb	2.38	0.73	7.61	1.92	14.42	8.69	8.64	4.72

TABLE 8. EMISSION RATES AND CONCENTRATIONS OF TOTAL PARTICULATE MASS AND SULFUR OXIDE GASES

Incinerator	Particulate mass		SO_2		H_2SO_4	
	kg/hr	mg/Nm^3	kg/hr	ppm	kg/hr	ppm
O	0.89	13.7	0.07	0.4	0.10	0.4
P	2.98	103.2	0.16	2.1	0.15	1.3
Q	0.094	9.4	0.30	11.1	0.022	0.6
R	2.13	199.6	3.34	92.4	0.31	7.0

TABLE 9. CONCENTRATIONS OF NITROGEN OXIDES AND HYDROCARBONS (ppm) IN SLUDGE INCINERATOR EMISSIONS

Incinerator	NO		NO_2		Hydrocarbons
	Range	Average	Range	Average	Range
O	8.8-105.8	31.4	3.2-61.3	22.7	6-7.2
P	18.9-139.9	102.5	0-63.5	26.2	3-6.4
Q	15.1-153.6	75.2	0-74.5	33.5	6.2-11.1
R	3.0-16.5	9.7	0-4.7	2.2	Not monitored

REFERENCES

1. Furr, A. K., A. W. Lawrence, S. S. C. Tong, M. S. Grandolpho, R. A. Hofstader, C. A. Bache, W. H. Gutenmann, and D. J. Lisk. Environ. Sci. Technol., 10, 683, 1976.

2. Fed. Regist., 42 (No. 160), 41776, Method 5 (August 18, 1977).

3. Fed. Regist., 42 (No. 160), 41786, Method 8 (August 18, 1977).

4. Bennett, R. L., J. Wagman, and K. T. Knapp, Adv. in X-ray Analysis, 19, 427, 1975.

5. Knapp, K. T., R. L. Bennett, R. J. Griffin, and R. C. Steward, in Proceedings of Workshop on Primary Sulfate Emissions from Combustion Sources, Vol. I, Measurement Technology, EPA-600/9-78-020a, 1977, p. 145.

6. Kellogg, R. B., N. F. Roache, and B. Dellinger. Anal. Chem., 53, 546, 1981.

7. Greenberg, R. R., W. H. Zoller, and G. E. Gordon. Environ. Sci. Technol., 15, p. 64, 1981.

APPENDIX A

INCINERATOR OPERATING CONDITIONS

The operating conditions including sludge loading and supplemental fuel used during the test periods are summarized in the following tables.

TABLE 10. SUMMARY OF INCINERATOR O OPERATING DATA

Date	Time	Hearth No. 1 temp. (°F)	Scrubber ΔP (inches H_2O)	Fuel oil used (gal/hr)	Sludge feed rate (lbs/hr)
11/27/79	0900	1340	8.7	0	11,756
	1000	1395	11.8	0	11,298
	1100	1335	11.2	0	11,874
	1200	1345	12.2	0	11,333
	1300	1430	12.4	0	11,426
	1400	1350	10.6	0	11,673
	1500	1340	11.5	0	11,619
	1600	1345	11.6	0	11,936
	1700	1390	12.0	0	14,623
	1800	1340	12.0	0	14,386
Average		1361	11.4	0	12,202
Total					122,024
11/28/79	0900	1540	12.0	0	14,286
	1000	1615	11.8	0	12,371
	1100	1400	10.3	0	13,145
	1200	1350	10.6	0	12,416
	1300	1350	10.0	0	11,444
	1400	1350	11.2	0	10,361
	1500	1420	11.8	0	10,589
	1600	1400	9.6	5.4	11,484
	1700	1540	13.6	5.4	13,317
	1800	1360	9.9	5.4	11,916
Average		1432	11.1	5.4	12,133
Total				16.2	121,329
11/29/79	0900	1160	12.5	0	12,233
	1000	1195	12.0	0	11,818
	1100	1215	12.9	0	12,176
	1200	1260	12.9	0	12,265
	1300	1190	13.5	0	12,306
	1400	1330	10.9	0	11,598
	1500	1320	10.2	0	11,004
	1600	1300	10.1	0	11,663
	1700	1290	11.4	0	9,108
	1800	1350	9.6	0	8,058
Average		1261	11.6	0	11,223
Total					112,229
11/30/79	0900	1415	10.1	0	10,498
	1000	1405	10.0	0	10,363
	1100	1390	10.2	0	10,451
Average		1403	10.1	0	10,437
Total					31,312

TABLE 11. SUMMARY OF INCINERATOR P OPERATING CONDITIONS

Date	Time	Hearth No.1 temp.(°F)	Scrubber pressure drop (inches H_2O)	Boiler steam flow (lbs/hr)	Natural gas used (ft^3)	Sludge feed rate (lbs/hr wet)
12/6/79	0800	1,130	3.8	4,000	8	
	0900	1,250	4	5,500	2	
	1000	1,250	3.8	5,000	2	
	1100	1,390	3	5,500	3	
	1200	1,300	3.8	5,000	3	
	1300	1,300	4	5,000	3	
	1400	1,310	4	5,500	3	
	1500	1,150	4.2	5,000	2	
	1600	1,400	4.2	6,000	2	
	1700	1,070	4	5,000	2	
	1800	1,170	4	5,000	2	
	1900	1,200	4	5,000	2	
Average		1,243	3.9	5,125	2.8	6,708
Total				61,500	34	73,778
12/7/79	0800	1,060	5	5,000	2	
	0900	990	4.2	5,000	2	
	1000	1,040	5	5,000	2	
	1100	1,160	4	5,000	2	
	1200	1,250	4	5,000	2	
	1300	1,060	4	5,000	2	
	1400	1,140	4	5,000	2	
	1500	1,200	4	5,000	2	
	1600	1,150	3.2	5,000	2	
	1700	1,320	4	5,000	2	
Average		1,137	4.1	5,000	2	8,625
Total				50,000	20	77,625

TABLE 12. SUMMARY OF INCINERATOR Q OPERATING DATA

Date	Time	Reactor gas discharge temp.(°F)	Reactor bed pressure drop (inches H_2O)	Fluidizing (air flow) SCFM	No. 2 fuel oil (gal/hr)	Total sludge input (lbs/hr dry)
12/11/79	0828	1245	37	4850	52	
	0928	1265	40	4500	22	
	1028	1290	40	4500	23	
	1128	1310	40	4500	23	
	1228	1340	40	4500	24	
	1328	1325	40	4550	19	
	1428	1330	40	4500	19	
Average		1301	39.6	4557	26	1,123
Total					182	7,863
12/12/79	0820	1345	40	5000	64	
	0917	1360	45	4800	12	
	1017	1385	42	5000	8	
	1117	1390	40	5100	7	
	1217	1410	40	5050	8	
	1317	1395	40	5050	7	
	1417	1400	40	5050	5	
	1517	1405	40	5050	10	
Average		1385	40.9	5013	15.1	1,882
Total					121	15,056
12/13/79	0827	1390	42	5100	27	
	1927	1330	42	5000	11	
	1027	1420	42	5050	18	
	1127	1435	42	5050	2	
	1227	1445	42	5050	2	
	1327	1450	42	5050	0	
	1427	1430	42	5050	0	
Average		1414	42	5050	8.6	2,522
Total					60	17,653

TABLE 13. SUMMARY OF INCINERATOR R OPERATING DATA

Date	Time	Sludge feed rate (lbs/hr)	Sludge moisture (%)
4/22/80	9:00-11:30	16,800	70
	1:30- 4:00	14,000	71
4/23/80	8:00-11:00	14,000	72
	11:00- 1:30	14,000	71
	1:30- 3:30	14,000	71
4/24/80	9:00-11:30	14,000	72
	12:00- 1:00	15,000	72
	1:30- 2:00	15,000	72

Average fuel oil burned was approximately 40 gal/hr.

APPENDIX B

PARTICULATE EMISSIONS DATA

The results of all Method 5 particulate emission tests are presented in the following tables. The results are based on the front half catch as specified in Reference 2. Standard conditions are defined as 68°F (20°C) and 29.92 inches of mercury, dry basis. No tests were made at incinerator Q before the scrubber due to the adverse temperature and pressure conditions.

TABLE 14. SUMMARY OF PARTICULATE EMISSIONS - INCINERATOR O

	Scrubber Inlet						
	Run IP1	Run IP2	Run IP3	Run IP4	Run IP5	Run IP6	Average
Particulate emissions (lbs/hr)	662.43	645.57	722.65	708.78	920.59	917.63	762.94
Stack gas flow rate (scfm)	32,754	28,598	35,216	33,558	31,895	31,009	32,172
Stack gas temperature (°F)	1,264	1,336	1,398	1,257	1,287	1,305	1,308
% O_2	13.2	11.3	12.1	12.6	11.5	12.0	12.1
% CO_2	7.0	7.6	7.5	7.5	8.1	7.1	7.5
% Isokinetic	88.0	102.4	97.4	97.7	99.8	102.1	97.9

	Scrubber Outlet						
	Run OP1	Run OP2	Run OP3	Run OP4	Run OP5	Run OP6	Average
Particulate emissions (lbs/hr)	3.17	2.43	1.48	2.14	1.97	0.59	1.96
Stack gas flow rate (scfm)	41,309	38,933	31,867	38,668	28,845	34,584	37,368
Stack gas temperature (°F)	167	149	178	119	165	159	156
% O_2	15.3	15.3	15.3	16.0	17.0	15.5	15.7
% CO_2	6.0	6.0	6.0	4.2	4.0	5.0	5.2
% Isokinetic	78.7	94.2	97.0	94.6	92.7	96.9	92.4

TABLE 15. SUMMARY OF PARTICULATE EMISSIONS - INCINERATOR P

	Scrubber Inlet					
	Run IP1	Run IP2	Run IP4	Run IP5	Run IP6	Average
Particulate emissions (lbs/hr)	17.77	38.52	68.72	74.27	56.06	51.07
Stack gas flow rate (scfm)	6,670	6,834	9,779	9,013	8,653	8,190
Stack gas temperature (°F)	439	454	469	465	468	459
% O_2	15.3	15.3	18.5	15.3	15.3	15.9
% CO_2	6.8	6.8	5.0	6.8	6.8	6.4
% Isokinetic	99.5	100.9	99.9	100.3	103.4	100.8

	Scrubber Outlet				
	Run OP1	Run OP2	Run OP4	Run OP5	Average
Particulate emissions (lbs/hr)	2.36	2.04	7.72	14.14	6.56
Stack gas flow rate (scfm)	12,442	15,604	20,813	16,527	16,346
Stack gas temperature (°F)	141	128	125	133	132
% O_2	12.0	12.0	11.3	11.3	11.6
% CO_2	5.0	5.0	3.0	3.0	4.0
% Isokinetic	112.7	106.6	103.3	100.4	105.8

TABLE 16. SUMMARY OF PARTICULATE EMISSIONS - INCINERATOR Q

	Scrubber Outlet							
	Run OP1	Run OP2	Run OP3	Run OP4	Run OP5	Run OP6	Run OP7	Average
Particulate emissions (lbs/hr)	0.25	0.20	0.23	0.30	0.24	0.13	0.11	0.21
Stack gas flow rate (scfm)	5,937	5,755	5,858	6,157	6,242	5,565	5,817	5,817
Stack gas temperature (°F)	62	81	81	94	93	97	94	86
% O_2	12.3	12.3	12.3	9.0	9.0	9.5	9.5	10.6
% CO_2	5.7	5.7	5.7	7.7	7.7	7.5	7.5	6.8
% Isokinetic	87.4	87.7	83.4	101.4	98.4	98.4	97.6	93.4

TABLE 17. SUMMARY OF PARTICULATE EMISSIONS - INCINERATOR R

	Scrubber Inlet						
	Run IP1	Run IP2	Run IP3	Run IP4	Run IP5	Run IP6	Run IP7
Particulate emissions (lbs/hr)	9.58	30.0	196.29	184.68	156.47	38.96	57.16
Stack gas flow rate (scfm)	3924	3448	7920	8276	8672	4335	3474
Stack gas temperature (°F)	696	694	803	768	753	774	696
% O_2	10.3	10.3	14.7	13.1	14.0	8.1	8.3
% CO_2	7.0	7.0	4.7	5.7	6.1	9.5	9.6
% Isokinetic	127.2	108.6	91.8	103.1	99.8	118.2	125.0

	Scrubber Outlet							
	Run OP1	Run OP2	Run OP3	Run OP4	Run OP5	Run OP6	Run OP7	Run OP8
Particulate emissions (lbs/hr)	3.49	2.00	2.12	1.64	1.54	3.30	10.51	14.35
Stack gas flow rate (scfm)	6227	6315	11945	11486	11019	5441	5727	6118
Stack gas temperature (°F)	132	135	150	148	146	150	144	139
% O_2	11.4	11.6	11.5	11.5	11.5	14.8	14.8	11.3
% CO_2	7.9	7.6	7.7	7.7	7.7	5.8	5.8	7.7
% Isokinetic	94.5	88.9	103.5	109.9	113.0	116.0	115.3	107.9

APPENDIX C

SULFUR DIOXIDE AND SULFURIC ACID MIST EMISSIONS DATA

The summary of SO_2 and SO_3 data obtained at the sludge incinerators before and after the scrubbers is presented in the following tables. At Incinerator Q, no inlet sampling was made due to the adverse inlet gas temperature and pressure conditions.

TABLE 18. SUMMARY OF SULFUR DIOXIDE AND SULFURIC ACID MIST EMISSIONS - INCINERATOR O

Date	Time	Run number	Stack gas flow rate (scfm)	SO_2 Emissions			H_2SO_4 Emissions		
				lb/DSCF* x 10^{-5}	lb/hr	Conc. ppm	lb/DSCF* x 10^{-5}	lb/hr	Conc. ppm
1979		Inlet							
11/27	1429	IP1	32,754	2.796	54.95	168	0.083	1.64	3.28
11/28	1158	IP2	28,598	3.541	60.75	213	0.011	1.90	4.36
11/28	1435	IP3	35,216	3.311	69.96	199	0.052	1.11	2.06
11/29	0845	IP4	33.558	3.233	65.10	195	0.255	5.13	10.02
11/29	1255	IP5	31,894	3.206	61.35	193	0.071	1.36	2.78
11/30	0925	IP6	31,009	3.117	57.99	188	0.080	1.48	3.13
		Outlet							
11/27	1434	OP1	41,309	0	0	0	0.003	0.008	0.13
11/28	1100	OP2	38,932	0.001	0.003	0.06	0.026	0.602	1.01
11/28	1447	OP3	31,867	0.010	0.168	0.59	0.015	0.278	0.57
11/29	0849	OP4	38,668	0.020	0.446	1.16	0.002	0.004	0.07
11/29	1256	OP5	38,845	0.008	0.176	0.45	0.002	0.004	0.08
11/30	0930	OP6	34,584	0.002	0.004	0.12	0.009	0.184	0.35

*Standard cubic feet at 68°F and 29.92 inches of Mercury, dry basis

TABLE 19. SUMMARY OF SULFUR DIOXIDE AND SULFURIC ACID MIST EMISSIONS - INCINERATOR P

Date	Time	Run number	Stack gas flow rate (scfm)	SO_2 Emissions			H_2SO_4 Emissions		
				lb/DSCF* x 10^{-5}	lb/hr	Conc. ppm	lb/DSCF* x 10^{-5}	lb/hr	Conc. ppm
1979		Inlet							
12/6	1115	IP1	----------	----------	----------	Void	----------	----------	----------
12/6	1350	IP2	6,834	4.482	18.379	270	0.046	0.188	1.80
12/6	1505	IP3	----------	----------	----------	Void	----------	----------	----------
12/7	0830	IP4	9,779	2.940	17.247	177	0.011	0.065	0.44
12/7	1015	IP5	9,013	3.470	18.762	209	0.054	0.294	2.14
12/7	1250	IP6	8,653	3.342	17.350	201	0.032	0.165	1.25
		Outlet							
12/6	1204	OP1	12,443	0	0	0	0.028	0.021	1.08
12/6	1655	OP2	15,604	0.002	0.015	0.096	0.061	0.57	2.39
12/7	0902	OP3	19,256	0.059	0.686	3.58	0.032	0.37	1.25
12/7	1227	OP4	20,813	0.075	0.940	4.53	0.011	0.14	0.46

*Standard cubic feet at 68°F and 29.92 inches of Mercury, dry basis

TABLE 20. SUMMARY OF SULFUR DIOXIDE AND SULFURIC ACID MIST EMISSIONS - INCINERATOR Q

Date	Time	Run number	Stack gas flow rate (scfm)	SO_2 Emissions lb/DSCF* x 10^{-5}	SO_2 Emissions lb/hr	SO_2 Emissions Conc. ppm	H_2SO_4 Emissions lb/DSCF* x 10^{-5}	H_2SO_4 Emissions lb/hr	H_2SO_4 Emissions Conc. ppm
(No inlet tests at this site)									
12/11	1005	OP1	5,937	0.008	0.278	4.70	0.006	0.021	0.23
12/11	1130	OP2	5,755	0.008	0.282	4.92	0.004	0.012	0.14
12/11	1316	OP3	5,858	0.010	0.336	5.75	0.005	0.017	0.19
12/12	1100	OP4	6,151	0.208	0.770	12.55	0.058	0.213	2.27
12/12	1300	OP5	6,242	0.224	0.837	13.46	0.007	0.026	0.27
12/13	1205	OP6	5,565	0.328	1.096	19.75	0.010	0.035	0.41
12/13	1331	OP7	5,203	0.280	0.875	16.88	0.008	0.026	0.33

*Standard cubic feet at 68°F and 29.92 inches of Mercury, dry basis

TABLE 21. SUMMARY OF SULFUR DIOXIDE AND SULFURIC ACID MIST EMISSIONS - INCINERATOR R

1980	Time	Run number	Stack gas flow rate (scfm)	SO_2 Emissions lb/DSCF* x 10^{-6}	SO_2 Emissions lb/hr	SO_2 Emissions Conc. ppm	H_2SO_4 Emissions lb/hr
Scrubber Inlet							
4/22	0935	IP1	3924	130.4	31.03	785.3	2.58
4/22	1405	IP2	3448	132.6	27.50	798.4	2.71
4/23	0850	IP3	7920	74.4	35.54	447.8	1.78
4/23	1200	IP4	8278	75.5	37.88	454.6	1.89
4/23	1430	IP5	8672	69.1	35.90	416.4	1.94
4/24	1005	IP6	4335	165.5	43.03	996.5	2.09
4/24	1200	IP7	3474	156.4	31.69	941.7	3.86
Scrubber Outlet							
4/22	0930	OP1	6228	11.8	4.36	70.8	0.26
4/22	1405	OP2	6315	12.5	4.70	75.3	0.33
4/23	0848	OP3	11945	6.7	4.75	40.2	1.52
4/23	1201	OP4	11486	20.3	13.87	122.3	0.92
4/23	1420	OP5	11019	17.0	11.17	102.6	0.68
4/24	0935	OP6	5445	31.1	10.06	187.2	0.74
4/24	1200	OP7	5729	8.1	2.75	48.6	1.59

*Standard cubic feet at 68°F and 29.92 inches of Mercury, dry basis

APPENDIX D

NITROGEN OXIDES EMISSIONS DATA

The following table shows the scrubber outlet concentrations for NO, NO_2, and NO_x during the testing periods at the four incinerators. Averages for each 20 min were determined from the Teco instrument strip charts. The average values for each day represent the mean of those 20-min averages.

Table 22. NITROGEN OXIDES EMISSIONS

Plant	Date	Average ppm		
		NO	NO_2	NO_x
O	11/27/79	72.8	13.2	86.0
	11/28/79	41.7	42.3	71.2
	11/29/79	10.4	21.0	32.4
	11/30/79	10.4	22.1	24.8
P	12/6/79	96.2	15.1	111.3
	12/7/79	105.0	30.6	135.7
Q	12/11/79	136.3	62.1	202.6
	12/12/79	46.3	23.6	72.3
	12/13/79	40.6	14.2	55.9
R	4/23/80	15.3	2.6	18.0
	4/24/80	3.5	2.3	5.9